Design and Development of Mass Optimised Latching Solenoid Valve for Chandrayaan-2 Lander Propulsion

Venkata Sunil Sai Nukala, Subrata Chakrabarti, D. Venkittaraman and M. Radhakrishnan

Abstract Chandrayaan-2 lander propulsion system employs a bipropellant thruster with a throttleable flow control valve (TCV) to vary the thrust produced by 800 N engines. A latching solenoid valve was proposed downstream of TCV to precisely admit/cut-off propellant supply to the engine as the latter does not inherently possess stringent leak tightness characteristics. The proposed valve employs a flexure guided plunger assembly to facilitate both continuous and pulse mode operation of the engine while preventing the possibility of cold welding/stiction between the sliding parts under space environment. A latching type of solenoid configuration was selected with balanced loading and permanent magnets to complement the solenoid in reducing the mass when compared to a conventional solenoid valve for the same application. In the selected configuration, switching of the valve position is accomplished by energising the solenoid coil and latching in the commanded position with the help of permanent magnets. Thus, the solenoid valve does not require continuous external supply, which results in negligible coil heating and very low power consumption. Two sets of proto models were realised which had undergone performance tests, 10,000 cycles of operation and 100 s duration hot test satisfactorily.

Keywords Propellant flow control · Solenoid · Permanent magnet · Flexure

1 Introduction

Chandrayaan-2 lander mission requires a liquid engine which can throttle to vary the thrust produced to facilitate de-boost and soft landing on the lunar surface. The thrust produced by 800 N engine is varied from 100 to 40% by throttling the propellant flow rate using a throttleable flow control valve (TCV). TCV does not inherently possess stringent leak tightness characteristics. Hence, a latching solenoid valve is proposed downstream of TCV to precisely admit/cut-off propellant supply to 800 N engine.

V. S. S. Nukala (✉) · S. Chakrabarti · D. Venkittaraman · M. Radhakrishnan
Control Systems and Components Entity, Liquid Propulsion Systems Centre, ISRO, Thiruvananthapuram, Kerala 695 547, India

PSR. S. Sastry et al. (eds.), *Advances in Small Satellite Technologies*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1724-2_5

Latching solenoid valve (Fig. 1) is basically a solenoid-operated shut-off valve with latching provision in the commanded position. Each bipropellant thruster has two valves (fuel and oxidiser) which are identical and is designed for the working medium with higher density. Electromagnetic flux produced by the solenoid is required to shift the position of the valve [2], and permanent magnetic flux is used for latching in the commanded position [3]. Breif specifications of the valve is given in Table 1.

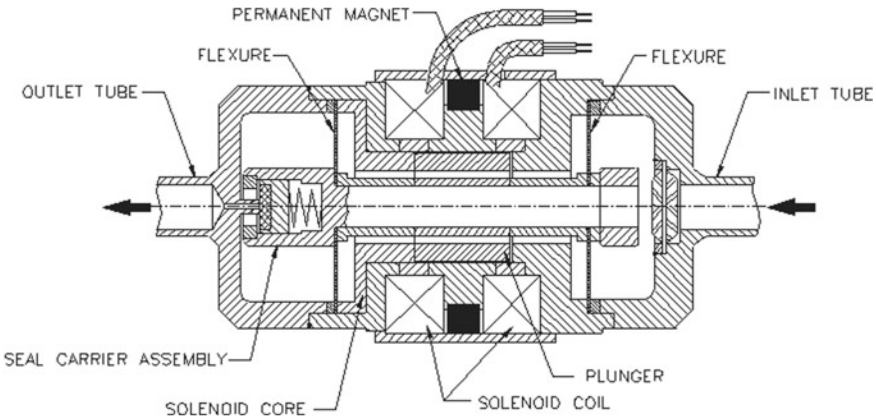


Fig. 1 Isolation latch valve

Table 1 Brief specifications of the valve

Sl No	Parameter	Specification
1	Working fluid	N_2O_4, MMH
2	Flow rate	162 g/s of oxidiser, 98 g/s of fuel
3	Maximum operating pressure	24 bar
4	Pressure drop at 162 g/s flow rate of oxidiser	3.5 bar
5	Working temperature	−7 to 60 °C
6	Supply voltage at coil terminal	21–14 VDC
7	Pull-in voltage (open and close)	≤11 VDC
8	Response time at 24 bar and 28 VDC	≤5 ms
9	Internal leakage at 24 bar	$\leq 1 \times 10^{-5}$ sccs of GHe
10	External leakage at 24 bar	$\leq 1 \times 10^{-6}$ sccs of GHe
11	Unit mass	≤220 g

2 Configuration

2.1 Description of Design

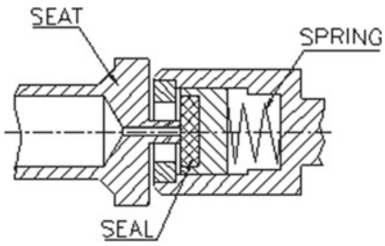
The latch valve has an axial configuration permitting straight flow of propellant through the valve. In order to accomplish precise guidance and sliding-free movement of the plunger inside solenoid bobbin bore, moving elements are suspended on a seal carrier assembly supported by flexures. This arrangement also results in minimising contaminant generation during valve actuation and improves fatigue life. Flexure (Fig. 2) is a flat spring designed to achieve required force–deflection characteristics, acts as a beam with fixed ends and ensures that moving elements are insensitive to lateral vibration loads. Stress analysis of the flexure is carried out, and the desired cyclic life is ensured in the design using the Soderberg criteria which inherently guards against yielding and is considered to be more conservative. Flexures have been calibrated and qualified for the intended number of actuations.

This method of guidance of plunger assembly facilitates both continuous and/or pulse mode operation of the 800 N Engine while preventing the possibility of cold welding or stiction between the sliding pair under space environment is compared to a direct sliding plunger type of valve, nor any coatings are required.

The port diameter is determined by the oxidiser flow requirements (162 g/s). Port diameter of 3.2 mm is selected, and corresponding valve stroke is provided accounting for the swell in soft seal material (PTFE) due to the thermal expansion and propellant wetting. Sealing is achieved by a flat PTFE seal pressing against a flat raised land-type stainless steel seat. PTFE seal element is preloaded with a helical spring in the valve closed condition. This floating spring configuration as depicted in Fig. 3 assures optimum seat bearing stress, self-alignment between the sealing surfaces. Inlet pressure generates additional interface sealing load. The seat stress provided should be adequate to permit sealing in unpressurised condition and at the same should be within the elastic limit at the operating pressure. For the present

Fig. 2 Flexure

Fig. 3 Floating spring configuration



design, maximum seat stress of 1.07 kg/mm^2 is provided which is within the yield limit for PTFE.

Solenoid bobbin comprises of soft magnetic material and non-magnetic material electron beam welded to form the magnetic circuit. AISI 446 is selected as the core material owing to its long-term compatibility with the propellants coupled with reasonably good magnetic properties. Non-linear BH characteristics of the core material are shown in Fig. 4.

Two coils are provided: one for opening and the other for closing the valve as shown in Fig. 5. The two coils are potted and hermetically sealed to prevent the entry

Fig. 4 Nonlinear BH curve for AISI 446

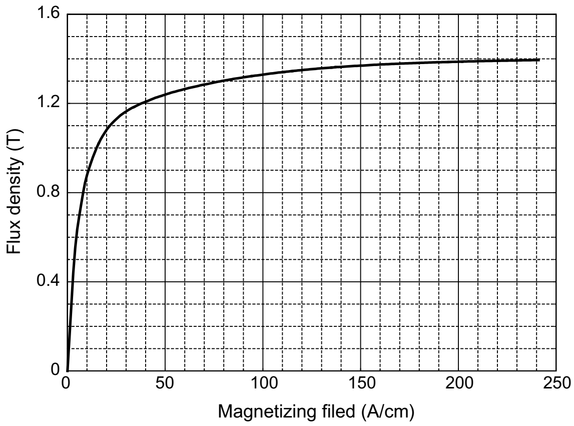
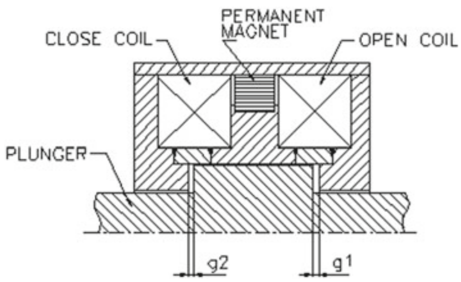


Fig. 5 Latching actuator schematic



of propellant vapours into the coil cavity. Electrical redundancy is available in the latch valve design without the incorporation of additional coils. If closing coil fails, valve can be closed by commanding open coil with reverse polarity. Similarly, the valve can be opened by commanding close coil with reverse polarity.

Five numbers of arc-shaped radially polarised samarium cobalt permanent magnets are employed to keep the valve latched in open/close position [3]. Permanent magnet is hermetically sealed from the working medium. Hence, no compatibility issues are associated with the selection of permanent magnetic material. Resultant force offered by the selected magnets is resistant to launch vibration and shock to prevent de-latching of the plunger from the commanded position. A 40-micron (abs) pleated disc filter is provided at the valve inlet. This ensures that the valve is contamination tolerant in achieving the stringent leakage specifications.

Thus, the latching type of solenoid configuration with balanced loading and permanent magnets to complement the solenoid optimises the actuator size when compared to a conventional solenoid valve for the same application.

All joints in the valve are electron beam welded. External leakage achieved through the valve is better than 1×10^{-6} sccs.

3 Principle of Operation

Latching solenoid valve is normally closed. Plunger remains latched in the last commanded position with the aid of flux emanated from permanent magnets.

3.1 Open Coil Energised

In the valve closed position, permanent magnet attracts the plunger and latches it to the pole piece with air gap g2 = 0, decoupling the closing spring force from the magnetic latch force. This electromagnetic actuator employs a radially polarised permanent magnet assembly to affect latching in both open and close positions. Two solenoid coils are provided to switch the plunger to the desired position. To open the valve, a short square wave voltage pulse is given to the open coil. This reduces the flux at the close pole piece (g2) and builds up at the open pole (g1) as shown in Fig. 6 [4] . When the attracting force exceeds the net closing forces with a margin, plunger moves towards open pole piece. After a small amount of pre-travel, the plunger assembly contacts the seal, overcomes the spring force and opens the valve. Plunger latches to the open pole piece, closing the air gap g1 and the valve is kept open. Electrical power may be terminated, and the plunger latches in the open position.

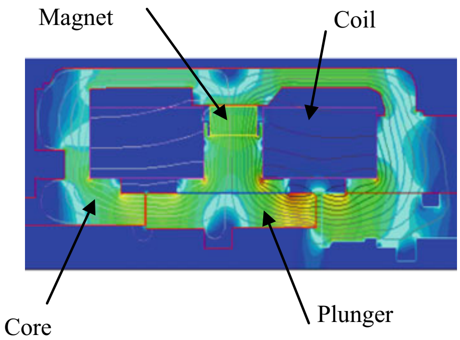


Fig. 6 Flux distribution—open coil energised

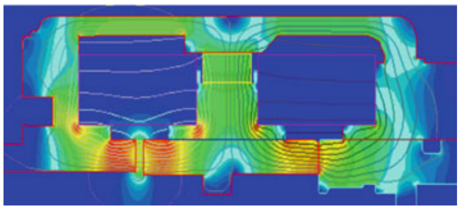


Fig. 7 Flux distribution—close coil energised

3.2 Close Coil Energised

To close the valve, a similar square wave voltage pulse is given to the close coil. This creates a magnetic flux which opposes the flux from the permanent magnet at air gap g1 and adds to the permanent magnet flux at the other air gap g2 as shown in Fig. 7 [4] . When the attractive force at gap g2 becomes large enough, plunger is attracted towards the close pole piece and the air gap g2 approaches zero. Power may then be terminated. For the present design, air gaps g1 and g2 are kept as 0.8 mm. Air gap is maintained within a tolerance band of 0.03 mm.

It may be noted that the poppet contacts the seat first during the closing process and the plunger over travels and latches to the close pole piece. This reduces the seat bearing stress, improves seal life and allows seal to align with seat under the spring load.

4 Testing

Two numbers of prototype valves were assembled and subjected to extensive developmental tests (Table 2) and the design parameters like operation at 24 bar inlet pressure, leak tightness under all operating conditions, dry coil exitation at rated voltage [1] valve response times were validated. Pull-in voltage measured for open

Table 2 Developmental test matrix

Sl No	Test
1	Proof pressure test
2	Reference functional tests (a) Pull in voltage measurement (b) Response (c) Internal leakage (d) Stroke (e) Internal and external leak checks
3	Water calibration test
4	Dry excitation test (42 VDC, 120 s)
5	Performance test at −7 to 60 °C
6	Thermo vacuum test (−7 to 60 °C, 6 cycles)
7	Vibration test (20.89 g)
8	Shock test (50 g, 10 ms)
9	Life cycle test (10,000 cycles at 24 bar inlet pressure)

coil and close coil was less than 11 VDC, indicating adequate margins for valve operation.

During the water calibration test, pressure drop achieved was higher to meet the equivalent water flow rate. However, no reduction in valve stroke was observed. When the flow path was critically analysed, choking of the flow path between the flexure and the solenoid core was identified as the reason for the higher pressure drop, and the same was corrected to meet the mass flow rate and pressure drop requirements. Developmental tests as per the above test matrix were completed. In particular, significance is the temperature exposure test and life cycle test. Temperature exposure test, wherein the valve was subjected to various temperature conditions, envisaged during the mission by means of external heating. Design adequacy and performance margins were demonstrated under different temperature conditions. Life cycle test was carried out at 24 bar inlet pressure using de-ionised water to demonstrate the cyclic capability of the valve under the lowest pulse width (30 ms ON and 100 ms OFF). No degradation in performance was noticed. This test was limited to 10,000 cycles based on the end-user requirements. However, cyclic test can be extended as the moving elements are guided in flexures which ensure sliding free movement and consistent performance. Performance tests conducted after every stage of the test mentioned in the developmental test matrix were satisfactory.

5 Results and Discussion

Performance tests were carried out on two prototype valves realised. Pull-in voltage for opening and closing was measured to be 10.5 VDC against minimum supply voltage of 14 VDC. This ensures a sufficient margin exists for the valve operation.

Latching function in open and close positions was demonstrated. Latch force provided was adequate to hold the plunger to the respective pole piece during vibration simulation test. Valve opening and closing response times under operating conditions were better than 4.5 ms. Internal leak tightness achieved through the valve seating surface was 1.5×10^{-8} sccs using GHe medium. Water calibration test was carried out on the valve, and a pressure drop of 3.2 bar was observed for equivalent flow rate of oxidiser. The performance of the valve has been demonstrated successfully under extreme operating conditions (−7 °C and 60 °C). Post-cyclic (10,000) performance test results showed no degradation in the performance of the valves.

6 Conclusion

A latching solenoid valve with a flexure guided plunger is designed and developed for the supply/cut-off of propellants to 800 N engine. Switching of the valve position and latching in the commanded position have been successfully demonstrated under various operating environmental conditions. Latching type of solenoid design eliminates the requirement of continuous energisation of solenoid coil which results in negligible heating and very low power consumption. Thus, the present valve is capable of continuous and/or pulse mode operation. Developmental hardware has undergone water calibration, temperature exposure, cyclic actuations, vibration simulation test and 100 s duration test fire with 800 N engine satisfactorily. The performance of the valve is consistent throughout the developmental phase. Mass of the proto model was 210 g which is 40% of the mass of a conventional solenoid valve designed for the same application.

References

1. Angadi SV et al (2009) Reliability and life study of hydraulic solenoid valve. Part 2: Exp Study Eng Fail Anal 16:944–963
2. Roters Herbert C (1941) Electromagnetic devices. Wiley, New York
3. Parker RJ, Studders (1990) Permanent magnets and their application. Wiley, New York
4. Tao G et al (2002) Optimal design of the magnetic field of a high-speed response solenoid valve. J Mater Process Technol 129:555–558